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HEAT TRANSFER IN HELIUM II

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[Numbers in brackets refer to the bibliography. Figures and tables are appended.]

The results of a number of investigations of heat transfer in liquid helium II are analyzed and the limits of applicability of Landau's theory of the phenomenon of heat transfer and the motion of the normal component of helium II are established.

1. The theory of superfluidity developed by Landau [1] leads to the division of the equations of hydrodynamics into two systems, one of which describes the behavior of the normal component and the other, of the superfluid component of helium II [2]. The application of these equations to heat transfer is discussed in detail in a publication by the author [3]. The investigation of the question is based on the general proposition of the theory that the superfluid part moves toward a source of heat, carrying no entropy, while the normal part of the liquid moves away from the source, carrying heat with it.

The derivation of the basic relations is as follows. The mean velocity of the normal component can easily be calculated by the equation.

$$\overline{V_n} = \frac{W}{Q\rho} \qquad (1)$$

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where $\bar{v}_n$ is the mean velocity of the normal motion, ρ the density of helium II, Q the heat content of 1 gm of helium, and w is the density of heat flow.

If heat transfer occurs through a sufficiently narrow slit or capillary, then to equation 1 should be added two further eqrations. One of these is H. London's well-known formula [4] for the thermomechanical effect (the truth of which was first established experimentally by Kapitza [5]) giving the pressure difference Δp produced between the two ends of the slit by the difference ΔT in temperature applied across it:

$$\Delta p = \frac{\rho Q}{T} \cdot \Delta T \tag{2}$$

On the other hand, the motion of the normal component in a narrow slit, which for relatively small velocities can be supposed to be laminar flow, satisfies Poiseuille's general relation and in the particular case of a flat slit the pressure gradient is given by the equation

$$\frac{dp}{dx} = \frac{12\eta_n \bar{v}_n}{d^2} = \frac{12\eta_n}{d^3} \cdot \frac{W}{2\pi R \rho Q} \tag{3}$$

in which d denotes the slit width, η_n the viscosity of the normal component, and W the total heat flow given by $W = 2\pi Rwd$ where $2\pi R$ is the perimeter of the slit.

Combining all three equations, we come to the conclusion that the heat flow is connected with the temperature gradient by a linear relation.

$$W = \frac{2\pi R d^3 \rho^2 Q^2}{12\eta_n T} \cdot \frac{dT}{dx} \tag{4}$$

A precisely similar formula was recently obtained with the aid of exceedingly complicated and artificial calculations [6].

2. A considerable number of experimental investigations [7, 11, and others] has been devoted to a quantitative study of heat transfer in helium II. Not to mention the quantitative discrepancies which involve factors of as much as hundreds or thousands, the empirical relations obtained do not fit into the framework of the theory in any way at all, if only for the reason that in all these papers (with the exception only of Allen and Reekie [10]) there is an absence of proportionality between heat flow and temperature difference. Experimental results show that heat flow increases as the cube root of the temperature difference.

Moreover, for a constant temperature difference the heat flow as function of temperature passes through a maximum at about 1.9 degrees K, which certainly does not follow from the formulae given. For capillaries of diameters several tenths of a millimeter, it was established that heat flow is proportional to cross section and inversely proportional to length; while from equation 4 it follows that it should be proportional to slit width cubed times length (in the case of a flat slit), or to the 4th power of the diameter (in the case of a capillary of circular cross section).

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The exact quantitative comparison of the experimental facts about heat transfer with the predictions of the theory are, however, made difficult in view of the absence of any information about the true temperature dependence of the normal viscosity of helium II.

3. The first direct possibility of a quantitative check of the theory of heat transfer in helium II was given by a series of publications in 1947 [12, 14] and by investigations of the viscosity of the normal component of helium II carried out by the author [15] and others. In view of the fact that Keesom and Duyckaerts' measurements of heat transfer contain a serious methodological mistake, the results of their investigations are practically valueless and unsuitable for purposes of analysis.

For comparison of experimental data with theory for the case of slits of relatively large dimensions (5 and 10 microns) there remains the results of Mellink [13]. A study of the dependence of heat flow upon temperature difference in the region close to the origin shows that this dependence is strictly linear. It should be noted that for small powers no maximum "heat conductivity" was observed in the experiments [13]. However, when a temperature difference of definite value is reached, then heat transfer begins to increase appreciably slower and in this region the curve of temperature versus heat-flow clearly shows the maximum, which had been previously observed several times. Calculation of the speed of relative motion of the normal and superfluid components shows that heat flow's linear dependence upon temperature difference disappears when this speed reaches 15 - 20 cm/sec. This agrees with the values of critical velocities observed by a number of investigators for the flow of helium II in films, capillaries, and slits.

Thus a superficial analysis of the data of investigations [13] already shows that heat transfer takes place just as predicted by theory, and the disagreement of the results of past experiments must be related to the fact that the critical velocity has been exceeded.

However, theory and experiments in fact show still closer agreement. Indeed, substituting Millink's data [13] into equation 4 and using for the heat content and viscosity experimental values found by Kapitza [5] and the author [15], we obtain figures very close to those found in Mellink's investigations [13]. Such discrepancy as there is, amounting to some tens of percent, must be explained in the first place by errors in the determination of the slit dimensions, which according to the authors could amount to 20 percent. Since the slit width enters into equation 4 in the third power, such errors, not to mention others not taken into account, could lead to discrepancies of 70 percent. The very low accuracy with which such small temperature differences are measured should also be mentioned.

The experimental data taken from Millink [13] and also the values of heat flow calculated by equation 4 are calculated together in Table 1.

For comparison we have chosen the region of small heat flow in which the laws of superfluid motion are obviously obeyed. The numbers refer to the slits made in two polished surfaces separated from each other by distances of 10.5 and 5 microns with corresponding lengths 0.248 and 0.1 cm. The circumference of the ring-shaped slit is 7.5 cm. Thus comparison of experimental results with theory leads to the important conclusion that heat transfer in helium II, which is the touchstone for every theory of superfluidity in slits of given dimensions, is correctly described by Landau's theory within experimental error.

4. Keesom and Duyckaerts, and Mellin, particularly emphasize the proportionality existing between the London effect (pressure difference between the two sides of the slit) and heat flow. According to the graphs given in the quoted papers, this proportionality can be seen to be still maintained even when, owing

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to the transition through the critical velocity, the linear dependence between heat flow and temperature difference has long been destroyed. Such an assertion might lead (and in many cases has led) to the false conception that in passing through the critical velocity the viscosity of helium II remains unchanged. In fact, from equation 3 it immediately follows that the constancy of viscosity is a condition necessary for the preservation of a linear relation between $\triangle$ p and W.

Basing himself on the indications of the quoted authors, namely, on a linear relation between $\triangle$p and W, Gorter [16] obtained for the "supercritical region" an expression for a parameter, M, of mutual friction between the superfluid and normal components and even determined from experimental data the numerical value of the coefficient A entering into the equation:

$$M = A \rho_s \rho_n \cdot (V_s - V_n)^3 \qquad (5)$$

where A is of the order of 50 cm sec gm^{-1}. In fact, such a formula (it appears to us to be a completely mistaken one) can be obtained on the basis of the absolutely unsound evidence brought forward by Mellink and others. In reality, the pressure drop across the slit entering into equation 3 is made up of the two terms: hydrostatic pressure of a column of liquid h and the pressure difference h_1 between the saturated vapors existing at the surface of the liquid for different temperatures (h_1 expressed in centimeters of liquid helium). The latter term can reach quite appreciable magnitudes, particularly in conditions where the critical velocity appears to have been exceeded (Table 2). Thus the dependence of the difference in level upon heat flow, which the authors of this paper investigated, has no definite physicial significance and the linear relation obtained by them for all heat flows appears to be purely coincidental and in no way describes the processes going on. The true dependence of pressure difference upon heat flow, which dependence we obtained by taking into account the factors indicated, is shown in Figure 1, from which it is clearly apparent that in passing through a certain critical value of heat flow the total pressure difference not only does not remain constant, but also significantly changes course.

The viscosity calculated from equation 3 remains constant only for comparatively low heat flows, and beginning from a certain value of heat flow a very marked rise in the viscosity is observable. A typical dependence of viscosity upon heat flow (that is, really upon velocity) is shown in Figure 2 (See also Table 2). A discrepancy in the numerical values of this quantity in the case of slits of 10.5 and 5 microns as already indicated earlier can be explained by the inaccuracy in determination of the slit width. It should be noted that according to our measurements the viscosity of helium II at temperatures corresponding to Figure 2 is 1.12 x 10^{-5} poise, which agrees very well with the value (1.18 x 10^{-5} poise) obtained for a slit of 5 microns. (In order to follow the dependence of viscosity upon heat flow, we could use equation 4, as we have done, to compare experimental and theoretical values of heat flow. However, in view of the fact that the temperature difference could be measured in Kellink's experiments with far less accuracy than the pressure difference (in the calculation of $\triangle$ p, the temperature difference enters only as a correction term), it is preferable to use equation 3 to connect viscosity and heat flow. The same circumstance also explains the fact that the calculated values of heat flow have an appreciably larger scatter than the calculated values of η_n.)

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However, especially characteristic is the agreement between the temperature variation of viscosity as determined on the one hand from our experimental data and, on the other, from experiments [13] (Figure 3). Unfortunately, for temperatures about 1.9 degrees K, heat transfer is nearly always measured by Mellink in the "supercritical region" and his measurements are therefore not suitable for determining viscosity.

In this connection, the assertion of F. London [6], also repeated by Tisza [17], that the viscosity of helium II is independent of temperature and has a value 2×10^{-5} poise (that is, the value for the viscosity of helium I), becomes completely inexplicable.

Using this experimentally unfounded value of viscosity, F. London compares the experimental and theoretical values of heat transfer. However, in explaining the temperature variation of heat transfer, the authors of the quoted article use a different form of temperature dependence of viscosity, $\eta_n \backsimeq \sqrt{T}$, although on the basis of Kapitza's data and others they could have perfectly easily disproved both of these assumptions.

5. Knowing the relation between heat flow W and mean velocity $\bar{v}_n$ of the normal component (and, consequently, the maximum velocity, $v_{n\,max}$) and also the relation between the velocities of normal and superfluid motion, we can determine the critical velocity v_k from the critical value of the heat flow. In the particular case of a flat slit, we have v_n max $= 1.5\,\bar{v}_n$ and the following equation (6):

$$v_k = v_{n\,max} + v_s = 1.5\,\bar{v}_n + \frac{\bar{v}_n \rho_n}{\rho_s} = \frac{W}{\rho Q}(1.5 + \rho_n \qquad (6)$$

Analysis of the experimental data of the investigations [13] allows us to make some conclusions about the quantity v_k. These experiments in particular bring out the temperature dependence of critical velocity. Thus, for instance, in the temperature interval 1.32 to 2.05°, the critical velocity falls roughly from 60 cm/sec to 7 cm/sec; that is, about nine times. However, the scatter of the values obtained is so large that it would be difficult to construct a smooth curve.

London and Zilsel [6] supposed that the critical value reaches the quantity v_s, and from experimental data [12] they obtained for v_{sk} a quantity independent of temperature and of the order 1 cm/sec. This value (contrary to the authors' assertion) differs by a large factor from the values obtained by all other investigators.

6. Already in slits 5 microns' width there begin to appear phenomena connected with the mean free path of the quasi-particles taking part in heat transfer, which must be reflected in the magnitude of the apparent viscosity. Indeed, solving equation 3 for η_n and substituting Mellink's data [13] into it, we can construct a curve of the temperature dependence of viscosity for slits of various widths. In Figure 3 the full curve shows the relative values of viscosity (viscosity at T = 1.72 degrees K is taken as unity) according to our measurements. The squares represent the relative values of viscosity calculated from Mellink's experiments for a slit of 10.5 microns, width, while the circles refer to experiments with a 5-micron slit. As can be seen from the diagram, in the temperature interval from the lambda point to 1.5 degrees K the points lie well on the full curve for both slits. For lower temperatures at which the phonon's mean free path becomes appreciable, the points corresponding to the 5-micron slit lie below the curve.

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This effect, namely the diminution of apparent viscosity for decreasing temperature, is shown much more markedly in slits of a width of 0.15 to 1 micron. Figure 4 shows the temperature dependence of apparent viscosity in slits 0.3, 0.5, and 1 micron calculated from the quoted papers [14].

The diminution of apparent viscosity observed for decreasing slit dimensions shows that in these conditions we have the phenomenon of "slip" connected with the transition of a gas of thermal excitations (more correctly only its phonon part) into the Knudsen region. In connection with this, the heat transfer in narrow slits gives values much higher than to be expected from the theoretical notion discussed at the beginning of this article.

Unfortunately, the character of the temperature dependence of heat transfer observed by Meyer and Mellink in this range of dimensions of the slit has not yet found a strict quantitative explanation.

7. We consider the present article, analyzing the results of experiments carried out by other investigators, necessary for publication not only in view of the importance of heat transfer in the theory of superfluidity of helium II, but also because most authors in this kind of experimental work take obviously false paths in the discussion of their results. Thus for instance Keesom and Duyckaerts [12] and also London and Zilsel [6] in trying to look for an empirical law connect the temperature dependance of heat flow with slit width. Keesom and Duyckaerts [12] even present a special table in which each slit size is given its own temperature dependence of heat flow. The absence of a clear understanding of the character of the processes studied has lead authors of other papers [14] to assert that in helium II there are observed three types of "heat conduction." One, the basic type, is encountered in capillaries of diameters greater than 30 microns. The second, also a basic type, is encountered in capillaries of diameters less than one micron. Finally, the third, a mixed type, takes place in diameters between 30 and 1 microns. There is no need to waste time by proving in more detail the evident falseness of such views.

In all experiments on heat transfer in fine capillaries (the application of Landau's theory of heat transfer in free helium II, as will be shown in the following article, meets with certain difficulties), as can be seen from the arguments brought forward in the present article, it is important to have conditions such that the length of free path of thermal excitations should be small in comparison with the dimensions of heat transfer, and the relative velocity of motion between normal and superfluid components should not exceed its critical value.

In conclusion, the author expresses his gratitude to L. D. Landau for taking part in the discussion of the question concerned.

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[Tables and figures follow.]

Table 1

Comparison of Experimental Data With Theoretical Values of Heat Transfer, Calculated From Equation 4

Slit	T°K	ΔTx10³ °K	Wx10⁴ watt experimental	Wx10⁴ watt theoretical
10.5 microns, 2.48 mm	1.724	0.3	27.33	62.5
	1.724	0.45	43.5	93.2
	1.508	0.32	8.03	11.2
	1.832	0.05	12.49	20.7
5 microns, 1.00 mm	1.328	13.1	16.38	13.9
	1.714	0.6	25.8	30.9
	2.032	0.07	24.52	28.9

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Table 2

Thermomechanical Effect and Viscosity of the Normal Component as a Function of Heat Flow

Slit micron	Slit mm	T^oK	$W \times 10^4$ watt	$\Delta T \times 10^3$	h cm	$(h+h_1)$ cm	$\eta_n \times 10^5$ poise	Remarks
10.5	2.48	1.325	55.75	36.4	17.49	20.25	2.83	
10.5	2.48	1.725	8.82	0.1	0.28	0.315	1.71)	
		1.725	14.31	0.13	0.47	0.516	1.73)	η_n = 1.71x10-5
		1.724	27.33	0.3	0.88	0.985	1.73)	poise.
		1.724	45.5	0.45	1.37	1.53	1.69)	
		1.724	63.87	0.8	2.13	2.41	1.81)	Beyond the
		1.727	93.80	1.8	3.32	3.95	2.02)	critical
		1.726	125.3	3.8	4.61	5.94	2.26)	velocity
		1.731	159.9	6.7	5.79	8.13	2.44)	(super-criti-
		1.734	196.4	13.2	7.29	11.74	2.87)	cal region)
10.5	2.48	1.508	8.03	0.32	0.72	0.77	1.92)	
		1.514	63.76	4.4	5.67	6.33	1.99)	
		1.514	79.38	7.8	7.31	8.48	2.14)	ditto
		1.520	117.8	21.1	10.21	13.37	2.27)	
10.5	2.48	1.832	12.49	0.05	0.28	0.305	1.73	
5	1.00	1.328	16.38	13.1	10.4	15.14	1.49	
5	1.00	1.714	25.8	0.6	2.70	2.91	1.18	
		1.716	72.6	4.2	7.95	9.41	1.36)	ditto
		1.725	124.3	21.5	14.13	21.6	1.83)	
5	1.00	2.032	24.52	0.01	1.16	1.17	1.43	
5	1.00	1.220	0.412	1.2	0.76	0.83	2.20	
		1.222	1.87	5.1	3.00	3.30	1.92	η_n = 2.18x10-5
		1.213	3.17	12.8	6.18	6.92	2.38	poise.
		1.211	2.32	8.8	4.51	5.02	2.36	
		1.218	6.65	22.5	11.1	12.41	2.04	

Note: Calculated according to the experimental data of Mellink [13].

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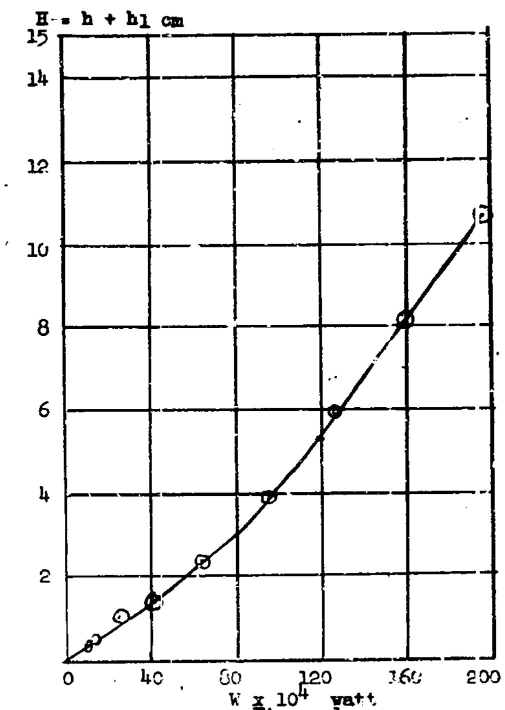

Figure 1

Dependence of the Thermomechanical Effect Upon the Heat Flow for 10.5-Micron Slit, T = 1.725°K (constructed from the experimental data of Millink [13]).

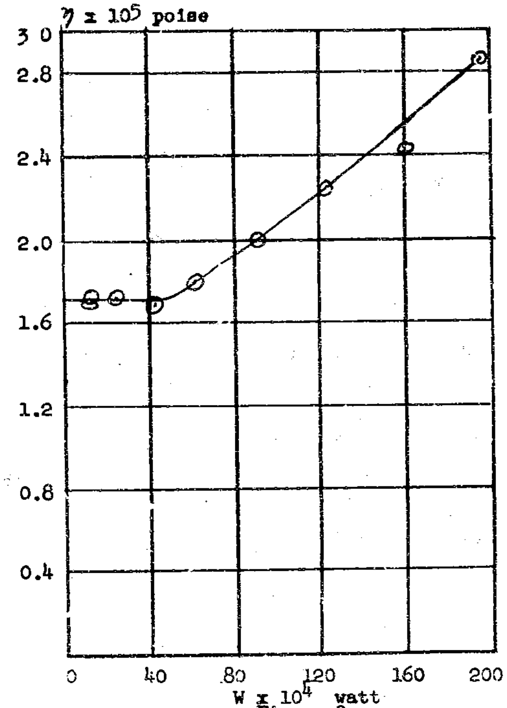

Figure 2

Dependence of Viscosity of the Normal Component of Helium II upon Heat Flow for 10.5-micron Slit, T = 1.725°K (constructed from the experimental data of Millink [13]).

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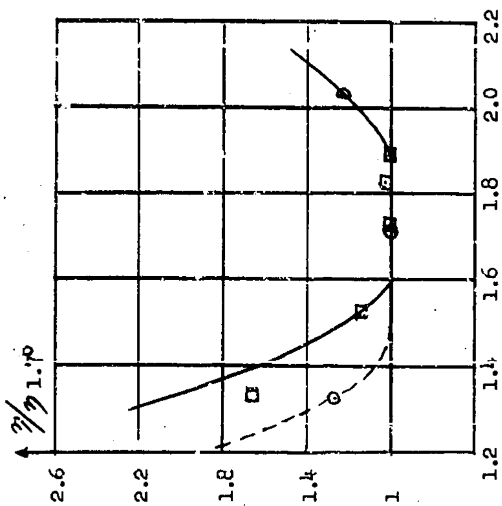

Figure 3

Temperature Dependence of Viscosity of the Normal Component. Full Curve According to Andronikashvili. Squares for 10.5-micron Slit; Circles for 5-micron Slit (according to the experimental data of Millink [13]).

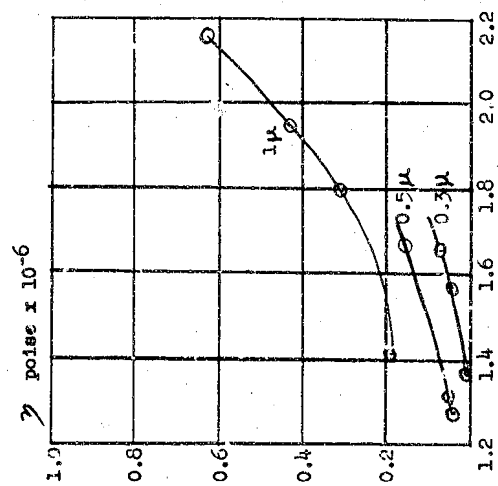

Figure 4

Temperature Dependence of the Apparent Viscosity for Thin Slits (constructed from the experimental data of Millink [13]).

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